

Summary of Research for ADP Grant NAG5-13055

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Listing of Basic Grant Information

Grant Title: X-Ray and Radio Studies of Black Hole X-Ray
Transients During Outburst Decay

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Proposal Summary

Black hole (BH) and black hole candidate (BHC) transients are X-ray binary systems that typically undergo bright outbursts that last a couple months with recurrence times of years to decades. For this ADP project, we are studying BH/BHC systems during the decaying phases of their outbursts using the *Rossini X-ray Timing Explorer (RXTE)*, the *Chandra X-ray Observatory*, and multi-wavelength facilities. These systems usually undergo state transitions as they decay, and our observations are designed to catch the state transitions. The specific goals of this proposal include: 1. To determine the evolution of the characteristic frequencies present in the power spectrum (such as quasi-periodic oscillations, QPOs) during state transitions in order to place constraints on the accretion geometry; 2. To contemporaneously measure X-ray spectral and timing properties along with flux measurements in the radio band to determine the relationship between the accretion disk and radio jets; 3. To extend our studies of X-ray properties of BHCs to very low accretion rates using *RXTE* and *Chandra*.

Results

The work performed under this proposal has been highly successful, allowing the PI to lead, direct, or assist in the preparation of 7 related publications in refereed journals and 6 other conference presentations or reports. These items are listed below, and the abstracts for the refereed publications have also been included. Especially notable results include our detailed measurements of the characteristic frequencies and spectral parameters of BH/BHCs after the transition to the hard state (see A1, A3, and A5) and at low flux levels (see A4). Our measurements provide one of the strongest lines of evidence to date that the

inner edge of the optically thick accretion disk gradually recedes from the black hole at low flux levels. In addition, we have succeeded in obtaining excellent multi-wavelength coverage of a BH system as its compact jet turned on (see A1). Our results show, somewhat unexpectedly, that the radio jet does not turn on until the hard X-ray emission is well past its peak hard state level, strongly constraining theoretical models for hard X-ray production and the spectrum emitted by the jet. Finally, the X-ray/radio results in A2 led us to propose a general picture about the relationship between jet production and X-ray spectral states.

A. Publications in Refereed Journals

A1. Kalemci, Tomsick, Buxton, Rothschild, Pottschmidt, Corbel, Brocksopp, & Kaaret, 2005, *Multi-wavelength Observations of the Galactic Black Hole Transient 4U 1543–47 During Outburst Decay: State Transitions and Jet Contribution*, ApJ, 622, 508.

Abstract: Multi-wavelength observations of Galactic black hole (GBH) transients during the state transitions and in the low/hard state may provide detailed information on the accretion structure of these systems. 4U 1543–47 is a GBH transient that was covered exceptionally well in X-ray and infrared (daily observations) and reasonably well in optical and radio during its outburst decay in 2002. When all the available information is gathered in the intermediate and the low/hard state, 4U 1543–47 makes an important contribution to our understanding of state transitions and the role of outflows on the high energy emission properties of black hole binaries. The evolution of the X-ray spectral and temporal properties and the IR light curve place strong constraints on different models for explaining the overall emission from accreting black holes. The overall spectral energy distribution is consistent with synchrotron origin for the optical and infrared emission, however, the X-ray flux is above the power-law continuation of the optical and infrared flux. The infrared light curve, the HEXTE light curve and the evolution of the X-ray photon index indicate that the major source of hard X-rays cannot be direct synchrotron radiation from an acceleration region in a jet for most of the outburst decay.

A2. Corbel, Fender, Tomsick, Tzioumis, & Tingay, 2004, *On the Origin of Radio Emission in the X-Ray States of XTE J1650–500 During the 2001–2002 Outburst*, ApJ, 617, 1272.

Abstract: We report on simultaneous radio and X-ray observations of the black hole candidate XTE J1650–500 during the course of its 2001–2002 outburst. The scheduling of the observations allowed us to sample the properties of XTE J1650–500 in different X-ray spectral states, namely the hard state, the steep power-law state and the thermal dominant state, according to a recent spectral classification of McClintock & Remillard. The hard state is consistent with a compact jet dominating the spectral energy distribution at radio frequencies; however, the current data suggest that its contribution as direct synchrotron emission at higher energies may not be significant. In that case, XTE J1650–500 may be dominated by Compton processes (either inverse Comptonization of thermal disk photons and/or SSC from the base of the compact jet) in the X-ray regime. We, surprisingly, detect a faint level of radio emission in the thermal dominant state that may be consistent with the emission of previously ejected material interacting with the interstellar medium, similar (but on a smaller scale) to what was observed in XTE J1550–564 by Corbel and co-workers. Based on the properties of the radio emission in the steep power-law state of XTE J1650–500 and taking into account the behavior of the other black hole candidates (namely GX 339–4, XTE J1550–564, and XTE J1859+226) while in the intermediate and steep power-law states, we are able to present a general pattern of behavior for the origin of radio emission in these two states that could be important for understanding the accretion-ejection coupling very close to the black hole event horizon.

A3. Rodriguez, Corbel, Kalemci, Tomsick, & Tagger, 2004, *An X-Ray Timing Study of XTE J1550–564: Evolution of the Low-Frequency Quasi-Periodic Oscillations for the Complete 2000 Outburst*, ApJ, 612, 1018.

Abstract: We report on *RXTE* observations of the microquasar XTE J1550–564 during a ~ 70 day outburst in 2000 April–June. We focus here on the temporal properties of the source and study the behavior of low-frequency (0.1–10 Hz) quasi-periodic oscillations (LFQPOs), which seem to be of different types. We focus on the so-called type C (according to the classification of Remillard and collaborators), which corresponds to a strong 0.1–6 Hz LFQPO found to be present during at least 17 observations. We find that the frequency of the QPO is better correlated with the soft X-ray (≤ 7 keV) flux than with the hard flux (≥ 7 keV). If soft X-rays represent the behavior of an accretion disk, the relation shows that the disk may set the LFQPO frequency. In two cases, the identification of the type of QPO is not straightforward. If the QPOs in those two cases are type A (or B), then we may be seeing the QPO type alternate between type C and type A (or B), and this may represent some rapid changes in the physical properties of the accretion flow before the system stabilizes and slowly decays toward the end of the outburst. On the other hand, if all the QPOs are of type C, we may be observing an inversion in the frequency versus flux relation similar to that seen in GRO J1655–40. We discuss the QPO behavior in the framework of theoretical models.

A4. Tomsick, Kalemci, & Kaaret, 2004, *Detection of Low-Hard State Spectral and Timing Signatures from the Black Hole X-Ray Transient XTE J1650–500 at Low X-Ray Luminosities*, ApJ, 601, 439.

Abstract: Using the *Chandra* X-ray Observatory and the *Rossi X-ray Timing Explorer*, we have studied the black hole candidate (BHC) X-ray transient XTE J1650–500 near the end of its 2001–2002 outburst after its transition to the low-hard state at X-ray luminosities down to $L = 1.5 \times 10^{34}$ erg s $^{-1}$ (1–9 keV, assuming a source distance of 4 kpc). Our results include a characterization of the spectral and timing properties. At the lowest sampled luminosity, we used an 18 ks *Chandra* observation to measure the power spectrum at low frequencies. For the 3 epochs at which we obtained *Chandra/RXTE* observations, the 0.5–20 keV energy spectrum is consistent with a spectral model consisting of a power-law with interstellar absorption. We detect evolution in the power-law photon index from $\Gamma = 1.66 \pm 0.05$ to $\Gamma = 1.93 \pm 0.13$ (90% confidence errors), indicating that the source softens at low luminosities. The power spectra are characterized by strong (20–35% fractional rms) band-limited noise, which we model as a zero-centered Lorentzian. Including results from an *RXTE* study of XTE J1650–500 near the transition to the low-hard state by Kalemci et al. (2003), the half-width of the zero-centered Lorentzian (roughly where the band-limited noise cuts off) drops from 4 Hz at $L = 7 \times 10^{36}$ erg s $^{-1}$ (1–9 keV, absorbed) to 0.067 ± 0.007 Hz at $L = 9 \times 10^{34}$ erg s $^{-1}$ to 0.0035 ± 0.0010 Hz at the lowest luminosity. While the spectral and timing parameters evolve with luminosity, it is notable that the general shapes of the energy and power spectra remain the same, indicating that the source stays in the low-hard state. This implies that the X-ray emitting region of the system likely keeps the same overall structure, while the luminosity changes by a factor of 470. We discuss how these results may constrain theoretical black hole accretion models.

A5. Kalemci, Tomsick, Rothschild, Pottschmidt, & Kaaret, 2004, *A Close Look at the State Transitions of Galactic Black Hole Transients during Outburst Decay*, ApJ, 603, 231.

Abstract: We characterize the evolution of spectral and temporal properties of several Galactic black hole transients during outburst decay using the data from well-sampled *Rossi X-Ray Timing Explorer* Proportional Counter Array observations close to the transition to the low/hard state. We find several global patterns of evolution for spectral and temporal parameters before, during, and after the transition. We show that the changes in temporal properties (sudden increase or decrease in the rms amplitude of variability) are much sharper than the changes in the spectral properties, and it is much easier to identify a state transition with the temporal properties. The spectral index shows a drop 3–5 days before the transition for some of our sources. The ratio of the power-law flux to the total flux in the 3–25 keV band increases close to the transition, which may mean that the system must be dominated by the coronal emission for the transition to occur. We also show that the power-law flux shows a sharp change along with the temporal properties during the transitions, which may indicate a threshold transition volume for

the corona. The evolution of the spectral and temporal properties after the transition is consistent with the idea that the inner accretion disk moves away from the black hole. Based on the evolution of spectral and temporal parameters and changes during the transitions, we discuss possible scenarios of how the transition is happening.

A6. Miller, Raymond, Fabian, Homan, Nowak, Wijnands, van der Klis, Belloni, Tomsick, Smith, Charles, & Lewin, 2004, *Chandra/High Energy Transmission Grating Spectrometer Spectroscopy of the Galactic Black Hole GX 339-4: A Relativistic Iron Emission Line and Evidence for a Seyfert-like Warm Absorber*, ApJ, 601, 450.

Abstract: We observed the Galactic black hole GX 339-4 with the *Chandra* High Energy Transmission Grating Spectrometer (HETGS) for 75 ks during the decline of its 2002-2003 outburst. The sensitivity of this observation provides an unprecedented glimpse of a Galactic black hole at about a tenth of the luminosity of the outburst peak. The continuum spectrum is well described by a model consisting of multicolor disk blackbody ($kT \sim 0.6$ keV) and power-law ($\Gamma \sim 2.5$) components. X-ray reflection models yield improved fits. A strong, relativistic Fe $K\alpha$ emission line is revealed, indicating that the inner disk extends to the innermost stable circular orbit. The breadth of the line is sufficient to suggest that GX 339-4 may harbor a black hole with significant angular momentum. Absorption lines from H- and He-like O and He-like Ne and Mg are detected, as well as lines that are likely due to Ne II and Ne III. The measured line properties make it difficult to associate the absorption with the coronal phase of the interstellar medium. A scenario wherein the absorption lines are due to an intrinsic AGN-like warm-absorber geometry-perhaps produced by a disk wind in an extended disk-dominated state-may be more viable. We compare our results to *Chandra* observations of the Galactic black hole candidate XTE J1650-500 and discuss our findings in terms of prominent models for Galactic black hole accretion flows and connections to supermassive black holes.

A7. Rodriguez, Corbel, & Tomsick, 2003, *Spectral Evolution of the Microquasar XTE J1550-564 over Its Entire 2000 Outburst*, ApJ, 595, 1032.

Abstract: We report on *RXTE* observations of the microquasar XTE J1550-564 during a ~ 70 day outburst in 2000 April-June. We present the PCA+HEXTE 3-200 keV energy spectra of the source and study their evolution over the outburst. The spectra indicate that the source transitioned from an initial low hard state (LS) to an intermediate state (IS) characterized by a ~ 1 crab maximum in the 1.5-12 keV band and then went back to the LS. The source shows a hysteresis effect such that the second transition occurs at a 2-200 keV flux that is half of the flux at the first transition. This behavior is similar to what is observed in other sources and favors a common origin for the state transitions in soft X-ray transients. In addition, the first transition occurs at an approximately constant 2-200 keV flux, which probably indicates a change in the relative importance of the emitting media, whereas the second transition occurs during a time when the flux gradually decreases, which probably indicates that it is driven by a drop in the mass accretion rate. In both LSs, the spectra are characterized by the presence of a strong power-law tail (Compton corona) with a variable high-energy cutoff. During the IS, the spectra show the presence of a ~ 0.8 keV thermal component, which we attribute to an optically thick accretion disk. The inner disk radius as inferred from disk blackbody fits to the energy spectrum remains relatively constant throughout the IS. This suggests that the disk may be close to its last stable orbit during this period. We discuss the apparently independent evolution of the two media and show that right after the X-ray maximum on MJD 51,662 the decrease of the source luminosity is due to a decrease of the power-law luminosity, at a constant disk luminosity. The detection of radio emission with a spectrum typical of optically thin synchrotron emission soon after the X-ray peak and the sudden decrease of the power-law luminosity at the same time may suggest that the corona is ejected and further detected as a discrete radio ejection.

B. Conference Presentations and Other Reports

- B1.** Tomsick, 2005, *Black Hole Spectral States and Physical Connections*, astro-ph/0509110, invited talk at "Spectra & Timing of Compact X-Ray Binaries," Mumbai, India
- B2.** Tomsick, 2004, *The Evolution of Accreting Black Holes in Outburst*, astro-ph/0401189, invited talk at "X-Ray Timing 2003: Rossi and Beyond," Cambridge, MA
- B3.** Kalemci, Tomsick, Rothschild, Pottschmidt, & Kaaret, 2004, *Transitions of black hole transients to the low/hard state under the microscope*, astro-ph/0312465, poster presentation at "X-Ray Timing 2003: Rossi and Beyond," Cambridge, MA
- B4.** Tomsick & Kalemci, 2003, *H 1743-322 (= IGR J17464-3213) Transition to the Hard State*, ATEL#198
- B5.** Smith, Kalemci, Tomsick, & Heindl, 2003, *State Transition of GX 339-4*, ATEL#120
- B6.** Kalemci, Tomsick, Rothschild, Corbel, Kaaret, & McClintock, 2002, *State Transition of the Black Hole Candidate 4U 1543-47*, ATEL#103